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Investigation of Crash Consequences for Common Child Restraint Misuse

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16. Abstract
Estimates of child restraint misuse rates in the United States range from 49 to 95 percent, but not all misuse modes have similar consequences in terms of restraint effectiveness. A series of laboratory sled tests was conducted to determine the effects of common misuses and combinations of misuses, including loose harness, loose installation, incorrect installation angle, incorrect belt path, loose/no tether, and incorrect harness clip usage. Three commercial convertible child restraint models loaded with the Hybrid III 3YO ATD and secured by either LATCH belt or lap seat belt were tested in rear-facing and forward-facing configurations on a modified FMVSS 213 bench. The response variables included ATD accelerations, excursions, and restraint kinematics. Belt/LATCH loads, tether loads, ATD kinematics, and restraint structural response data were also documented. A fractional factorial test design on eight factors was used to define an initial series of 32 tests. The analysis of that data determined the selection of conditions for the remaining 20 tests to focus on factors and interactions of high interest and significance.

In the rear-facing condition, misrouting the LATCH belt or seatbelt through the incorrect belt path was the only misuse that significantly affected outcomes of interest and was associated with high levels of undesirable CRS rotation. In forward-facing tests, loose installation and tether misuse had large adverse effects on three out of four key response variables. Because the results show that a rear-facing installation is more resistant to user error, they also provide support for extended rear-facing restraint use. The study provides strong evidence for prioritizing tight restraint installation and proper tether use for forward-facing restraints. In particular, use of the tether helped to reduce the adverse effects of loose installation or loose harness.

17. Key Word
child restraints, dynamic performance, misuse, FMVSS 213

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Background

Motor vehicle crashes are a leading cause of injury and death for children in the United States (Heron, 2016). Child restraint systems (CRS) are highly effective in preventing harm for pediatric automotive passengers. Research from the National Highway Traffic Safety Administration estimates that CRS use by children under 1 year of age (i.e., rear-facing, harness-equipped CRS) reduces the chance of fatality by 71 percent in passenger cars and by 58 percent in light trucks. CRS use by children 1 to 4 years old (primarily forward-facing, harness–equipped CRS) reduces the likelihood of fatality by 54 percent in passenger vehicles and 59 percent in light trucks (Kahane, 2015). Arbogast (2004) found that CRS equipped with a harness reduce the risk of injury by 78 percent over children restrained by seatbelt systems. These effectiveness numbers are for CRS "as used" in the real world, which often includes misuse.

CRS are most effective when properly used, but misuse of CRS is frequent. Misuse is most often defined as use of the CRS that does not adhere to the manufacturers' instructions, whether or not this deviation is associated with an expected decrement in occupant protection. Child restraint misuse rates of 72 percent to over 90 percent have been reported in the literature (Decina & Knoebel, 1997; Decina & Lococo, 2005; NHTSA, 2001; Decina et al., 2011). Several researchers have classified misuse severity using groupings such as minor/moderate/major or by calling out some misuses as "critical," meaning misuse that decrements the safety benefits of the CRS. The most common CRS misuses include: loose CRS installation (often due to unlocked seat belt), loose occupant harness, non-use of tether, mispositioned harness clip, incorrect recline angle, use of incorrect CRS belt paths and improper CRS selection for the child (Decina & Lococo, 2005; Arbogast, 2000: Decina et al., 2011). More than one misuse is often observed.

In May 2015 NHTSA released a study on CRS use that defined misuse as a use that decreases crash protection (Greenwell, 2015). This study estimated an overall CRS misuse rate of 46 percent, much lower than when misuse is defined as deviation from manufacturers' instructions. The most prevalent misuses documented by NHTSA were loose CRS installation, incorrect CRS angle, loose occupant harness, incorrect LATCH belt or seatbelt routing through CRS (i.e., wrong CRS belt path used), and seatbelt not locked. This study also observed a 61 percent usage of top tether straps in forward-facing harness CRS but did not include tether non-use in the misuse percentage, as regulations require that forward-facing child restraints must meet minimum standards without use of a tether.

The leading cause of serious injury to children in motor vehicle crashes is head, neck, and face injury due to contact with the vehicle interior (Sherwood, 2003; Arbogast, 2012). This indicates that a focus on reducing forward occupant excursion and reducing misuse modes that increase occupant head excursion (namely loose installation, loose harness, nonuse of tether, etc.) are key pathways to lower child injury and fatality rates.

Objectives

This study used dynamic sled testing to evaluate the effect of common CRS misuse modes and common combinations of misuse on anthropomorphic test device (ATD) excursion, kinematics, and injury response measures.

Methods

Convertible Child Restraints

Three convertible child restraint models were used for the test series: Graco MyRide, Evenflo SureRide 65XL, and Cosco Apt 40RF. The three CRS are shown in Figure 1. Convertible child restraints were selected because they can be used in either rear-facing or forward-facing configurations. In addition, all of the CRS had a rear-facing occupant mass limit of 18kg (40 lb) and a forward-facing occupant mass limit of 29 kg (65 lb).

Figure 1. Three tested CRS from left to right: Graco MyRide, Evenflo SureRide 65XL and Cosco Apt 40RF

Aside from the specific misuse tested, each seat was used per the manufacturer's instructions. Table 1 describes details of the CRS set-up conditions.

Table 1. CRS set-up details

		Evenflo SureRide	**Graco MyRide 65LX**	**Cosco Apt 40RF**
Forward-facing	**Harness slots**	3rd position down from top	1st position down from top	Top
	Splitter plate	Outer harness loops	Outer harness loops	
	Crotch strap	Forward slot	Not adjustable	Forward
	Orientation	Upright (foot extended)	Upright (two feet extended)	
Rear-facing	**Harness slots**	3rd down from top	1st position down from top	Top
	Splitter plate	Outer harness loops	Outer harness loops	
	Crotch strap	Forward slot	Not adjustable	Forward
	Orientation	Reclined (foot extended for correct use, retracted for too upright)	Reclined (both feet retracted)	

Test Bench

The dynamic tests were performed using a preliminary test bench design (shown in Figure 2) that represented a potential replacement for the FMVSS No. 213 frontal impact bench (hereafter referred to as the preliminary 213 bench). It consists of the vehicle seat portion of the side impact buck assembly described in the Notice of Proposed Rulemaking (NPRM) of Federal Docket #NHTSA-2014-0012, except the lower anchors (LAs) were placed 40 mm lower. The bench is mounted to the sled forward-facing without the intruding door assembly but with its height adjusted upward by 50 mm risers. The bench also differs from the NPRM specification in that the seat back has been extended upwards to create a longer/taller seat back support surface. This bench was mounted facing forward on the impact sled at The University of Michigan Transportation Research Institute. It was positioned so excursion measurements of ATDs with this bench would be consistent and comparable with those measured in tests performed on the current FMVSS 213 bench. The test bench was equipped with lower anchor bar instrumentation, so that load histories of the lower anchors were measured. Belt load cells were used to pretension and measure dynamic loads for the tether and lap belt.

Figure 2. Preliminary 213 bench used for the test series

ATD Selection, Data collection, and Positioning

The Hybrid III 3-year-old ATD (part 572, subpart P) was used to represent a large occupant of a rear-facing convertible as well as a mid-sized occupant of a forward-facing harness-equipped CRS. The ATD was instrumented with head and chest accelerometers. The current FMVSS 213 test protocol was used to place the CRS on the bench and the Hybrid III 3YO ATD in the CRS using the current 213 dummy positioning process (TP-213). A FARO arm 3D coordinate measurement system was used to document the position of the ATD, booster, and test bench landmark locations in each test. The seat belt, lower anchor and tether attachments were tensioned to 53-67 N (12-15 lbf) for the proper use conditions. The sled pulse used for testing was consistent across tests and close to that used for Standard 213 testing.

For each test, head and chest accelerations were measured and the corresponding injury criteria of the head injury criterion (HIC) and 3-ms chest clip were calculated. For rear-facing tests, initial and maximum CRS seatback angle was recorded. For forward-facing tests, head and knee excursions were measured and evaluated relative to the excursion limits required for testing with a tether, namely a limit of 710 mm for the leading edge of the head and 915 mm for the knee center.

Test Conditions

Based on the previous studies of CRS misuse, the misuse modes of interest for all installations were: harness tightness, installation tightness, harness retainer clip misuse, and incorrect belt path. For rearward facing installs, inappropriate installation recline was also explored. Tether use (no tether/loose tether/tight tether) was added as a factor for forward-facing installations. CRS model and securement method (LATCH belt/lap seat belt) were included to find out if the findings could be generalized to a larger range of situations.

The misuse conditions are illustrated in Figure 3 through Figure 8. The levels selected for the misuse factors were the following.

- Install tightness (Figure 3):
  - tight = 15 lbf belt tension,
  - loose = 4 inches of loose belt
- Harness tightness (Figure 4):
  - tight = snug per pinch test,
  - loose = 4 inches of loose harness
- Tether tightness (Figure 5):
  - tight = 15 lbf belt tension,
  - loose = 4 inches of loose belt
  - no tether
- RF Recline (Figure 6):
  - too upright = -15 degrees,
  - correct (per CRS instructions)
  - too reclined = +15 degrees
- Belt path (Figure 7):
  - forward-facing installation using rear-facing belt path
  - rear-facing installation using forward-facing belt path
- Harness Retainer Clip (Figure 8)
  - harness clip present
  - harness clip absent

Figure 3. Loose installation condition (50 mm loop of slack)

Figure 4. Loose harness condition (50 mm loop of slack distributed to both sides of harness)

(a)

(b)

(c)

Figure 5. Tether conditions – Tight (a), Loose (b - 50 mm loop of slack) and no Tether (c)

(a)

(b)

(c)

Figure 6. Recline angle - 15 deg too upright (a), Correct (b), 15 deg too reclined (c)

(a)

(b)

Figure 7. Incorrect belt routing - forward-facing using rear-facing belt path (a) and rear-facing using forward-facing belt path (b)

(a)

(b)

Figure 8. Harness retainer clip: present (a) or absent (b)

Due to the large number of factors of interest, a two-step analysis approach was employed. The first 36 runs explored the main effects and two-way interactions among the variables of interest using a fractional factorial design of eight variables. In addition, the first series included correct use runs of each of two CRS models in each orientation (forward- and rearward facing). After those data were analyzed to determine where more testing was needed to fully define the response, the remaining 21 tests were conducted. The second series also included the condition of “no tether” since this is often seen in the field. All data were analyzed using analysis of variance (ANOVA) and multiple regression techniques with JMP Pro 11.

Table 2. Matrix for CRS Misuse Series

TestID	Belt/ LA	CRS	Tether Tight FF/ incline RF	Harness clip y/n	Belt/LA looseness	RF/ FF	Misroute/ wrong belt path y/n	Harness looseness
Series 1								
NT1411	LA	Evenflo	loose	yes	loose	FF	no	loose
NT1412	LA	Evenflo	loose	yes	tight	FF	no	tight
NT1413	LA	Evenflo	tight	yes	loose	FF	no	tight
NT1414	LA	Evenflo	tight	yes	tight	FF	no	loose
NT1415	LA	Evenflo	loose	no	loose	FF	yes	tight
NT1416	LA	Evenflo	loose	no	tight	FF	yes	loose
NT1417	LA	Evenflo	tight	no	loose	FF	yes	loose
NT1418	LA	Evenflo	tight	no	tight	FF	yes	tight
NT1419	LA	Evenflo	tight	yes	tight	FF	no	tight
NT1420	LA	Graco	loose	yes	loose	FF	yes	tight
NT1421	LA	Graco	loose	yes	tight	FF	yes	loose
NT1422	LA	Graco	loose	no	loose	FF	no	loose
NT1423	LA	Graco	loose	no	tight	FF	no	tight
NT1424	belt	Graco	loose	yes	loose	FF	no	tight
NT1425	belt	Graco	loose	yes	tight	FF	no	loose
NT1426	belt	Graco	loose	no	loose	FF	yes	loose
NT1427	belt	Graco	loose	no	tight	FF	yes	tight
NT1428	belt	Graco	tight	yes	tight	FF	no	tight
NT1429	belt	Evenflo	tight	yes	loose	FF	yes	tight
NT1430	belt	Evenflo	tight	yes	tight	FF	yes	loose
NT1431	belt	Evenflo	tight	no	loose	FF	no	loose
NT1432	belt	Evenflo	tight	no	tight	FF	no	tight
NT1433	belt	Evenflo	too upright	yes	loose	RF	yes	loose
NT1434	belt	Evenflo	too upright	yes	tight	RF	yes	tight
NT1435	belt	Evenflo	too upright	no	loose	RF	no	tight
NT1436	belt	Evenflo	too upright	no	tight	RF	no	loose
NT1437	belt	Evenflo	correct	yes	tight	RF	no	tight
NT1438	belt	Graco	too reclined	yes	loose	RF	no	loose
NT1439	belt	Graco	too reclined	yes	tight	RF	no	tight
NT1440	belt	Graco	too reclined	no	loose	RF	yes	tight
NT1441	belt	Graco	too reclined	no	tight	RF	yes	loose
NT1442	LA	Graco	too reclined	yes	loose	RF	yes	loose
NT1443	LA	Graco	too reclined	yes	tight	RF	yes	tight

TestID	Belt/ LA	CRS	Tether Tight FF/ incline RF	Harness clip y/n	Belt/LA looseness	RF/ FF	Misroute/ wrong belt path y/n	Harness looseness
NT1444	LA	Graco	too reclined	no	loose	RF	no	tight
NT1445	LA	Graco	too reclined	no	tight	RF	no	loose
NT1446	LA	Graco	correct	yes	tight	RF	no	tight
Series 2								
NT1447	belt	Evenflo	tight	yes	tight	FF	no	tight
NT1448	belt	Evenflo	tight	yes	loose	FF	no	tight
NT1449	belt	Evenflo	tight	yes	tight	FF	no	loose
NT1450	belt	Evenflo	tight	yes	loose	FF	no	loose
NT1451	belt	Evenflo	loose	yes	tight	FF	no	tight
NT1452	belt	Evenflo	loose	yes	loose	FF	no	tight
NT1453	belt	Evenflo	loose	yes	tight	FF	no	loose
NT1454	belt	Evenflo	loose	yes	loose	FF	no	loose
NT1455	belt	Evenflo	none	yes	tight	FF	no	loose
NT1456	belt	Evenflo	none	yes	loose	FF	no	tight
NT1457	belt	Evenflo	none	yes	loose	FF	no	loose
NT1458	belt	Evenflo	none	yes	tight	FF	no	tight
NT1459	belt	Evenflo	tight	yes	tight	FF	yes	tight
NT1460	belt	Cosco	tight	yes	tight	FF	no	tight
NT1461	belt	Cosco	loose	yes	loose	FF	no	tight
NT1462	belt	Cosco	loose	yes	tight	FF	no	loose
NT1463	belt	Cosco	tight	yes	loose	FF	no	loose
NT1464	belt	Cosco	tight	yes	tight	FF	yes	tight
NT1465	belt	Cosco	correct	yes	tight	RF	yes	tight
NT1466	belt	Evenflo	correct	yes	tight	RF	yes	tight
NT1501	belt	Cosco	correct	yes	tight	RF	no	tight

Results

Overview

Table 3 summarizes the primary response variables collected during all forward-facing tests while Table 4 provides the response information for the rear-facing tests. Bolded data values indicate where the response variables exceed the limits set by the current version of FMVSS 213. In some of the rear-facing runs, over-rotation of the CRS allowed the ATD and CRS to contact the test buck in a way that would not be possible in an actual vehicle, and artificially increased the head acceleration measures and HIC. These data are marked with an asterisk and were excluded from the analysis. Analysis of the first 36 runs showed that securement method (LATCH belt or lap seat belt) had no effect and that the harness clip effect was too small to have practical importance to injury outcomes. As a result, these two variables were held constant for the second series of tests, so that other factors could be more completely explored.

When all the rear-facing and forward-facing data were combined, there was no evidence that rear-facing installations produced lower overall ATD acceleration levels. In the combined data, the only factor with a significant effect was loose installation that increased the 3ms chest clip level by 11 g ($P<0.0002$).

Table 3. Results of Forward-Facing Tests

Test ID	HIC (36 ms)	Chest *g*	Head Ex (mm)	Knee Ex (mm)	Structural Issues
NT1411	**1065.1**	**63.0**	**774**	883	
NT1412	736.6	50.4	641	780	
NT1413	543.6	49.1	603	791	
NT1414	550.4	45.2	594	750	
NT1415	957.7	54.8	717	783	Belt slid into crack on shell
NT1416	**1030.1**	51.1	698	700	Belt slid into crack on shell
NT1417	761.6	50.5	669	738	
NT1418	542.2	44.8	581	665	
NT1419	480.9	41.6	571	736	
NT1420	838.1	**68.3**	697	813	
NT1421	950.6	**60.6**	642	730	
NT1422	917.1	**68.3**	**771**	857	
NT1423	900.4	51.1	648	760	
NT1424	**1026.8**	**74.1**	694	840	
NT1425	820.8	58.0	657	788	
NT1426	**1272.1**	**76.3**	**750**	846	
NT1427	900	59.7	621	720	
NT1428	422	46.1	545	685	
NT1429	463.9	46.1	595	738	
NT1430	617.5	47.5	611	691	
NT1431	588.5	54.2	707	816	
NT1432	481	42.2	608	744	
NT1447	489.7	45.2	581	767	
NT1448	516.8	48.3	623	803	
NT1449	571.7	47.4	613	766	
NT1450	457.5	**60.4**	684	837	
NT1451	824	55.6	656	806	Foot intrudes into bottom of shell
NT1452	**1073.5**	**62**	716	887	Foot intrudes into bottom of shell
NT1453	**1021.2**	**60.8**	703	826	Foot intrudes into bottom of shell
NT1454	**1062.2**	**74.5**	**791**	**920**	
NT1455	**1148.6**	58.3	**746**	814	
NT1456	**1309.5**	**75.6**	**813**	906	
NT1457	**1332.3**	**77.2**	**837**	**919**	
NT1458	841.2	59.4	697	816	
NT1459	492.9	41.6	586	693	
NT1460	586.1	42.5	631	657	
NT1461	**1130.2**	**62.5**	808	831	
NT1462	732.3	42.7	710	707	
NT1463	508.3	51.9	**761**	753	Tether broke through back of CRS
NT1464	670.4	36.8	644	656	

Table 4. Results of Rear-Facing Tests

Test ID	HIC (36 ms)	Chest *g*	Initial SB Angle (deg)	Max SB Angle (deg)	Structural Issues
NT1433	727.4	40.3	18.8	**115**	Shell cracked at belt path holes
NT1434	388.3	35.5	16.8	**126.6**	Shell cracked at belt path holes
NT1435	682.3	53.9	21.1	47.45	Shell cracked at belt path holes and on legs.
NT1436	**1136.5**	47.6	22.0	41.7	
NT1437	806.6	53.0	32.1	43.1	
NT1438	**1084.9**	**74.4**	46.1	61.9	Crotch belt pulled through CRS Shell
NT1439	912.5	**61.0**	46.0	58.7	
NT1440	**3547.7***	**76.0**	47.3	**120.8**	
NT1441	**1294.8**	**61.7**	47.6	**119.3**	
NT1442	**3409.4***	**65.8**	52.7	**128.4**	
NT1443	**1906.7**	48.7	47.9	**126.3**	
NT1444	756.6	**62.6**	51.0	64.5	
NT1445	850.3	57.6	45.7	64.09	
NT1446	904.6	56.8	32.9	52.93	
NT1465	**2635.3***	**68.5**	37.8	**131.9**	
NT1466	**2171.0**	**73.0**	31.7	**125.6**	
NT1501	783.1	46.1	36.4	52.2	

*Indicates tests where the CRS contacted the non-vehicle like portions of the test buck and spurious high head acceleration data were recorded.

Forward-facing analysis

For the data from the forward-facing tests, the results of the multivariate analysis, shown in Table 5, found significant main effects for the following factors: loose tether, loose installation, loose harness, no harness clip, and CRS type. No effects were found for securement type (lower anchors/lap seat belt) or incorrect belt path. No two-way interactions were found between the variables. In this dataset, a properly used tether reduced head excursion by an average of 150 mm over the no tether condition. The misuse factors associated with decoupling the occupant from the vehicle seat all had effects in the expected direction, meaning that the misuses increased the response measures. The effect of harness clip, although statistically significant, is not large enough to have a practical significance in the field.

Table 5. Forward-facing Analysis

Main Effects	HIC 36 (36 ms)	Chest 3ms (g)	Head Ex (mm)	Knee Ex (mm)
Tether Loose	417 (P<0.0001)	14 *g* (P<0.0001)	83 mm (P<0.0001)	66 mm (P=0.0083)
Belt/LA Loose	161 (P=0.0069)	12 *g* (P<0.0001)	87 mm (P<0.0001)	93 mm (P<0.0001)
Harness Loose	-----	-----	57 mm (P<0.0001)	-----
Harness clip	-----	-----	3 mm (P=0.0082)	-----
CRS type	-----	-11 *g* (P=0.0004)	40 mm (P<0.0001)	-69 mm (P<0.0001)

The CRS type effect is best described as a difference in kinematics, with the Cosco systematically having higher head excursions, lower knee excursions and lower chest accelerations. These differences did not interact with other effects, but shifted the baseline for the results from this CRS. Figure 9 shows peak excursion photos demonstrating the differences between two CRS models.

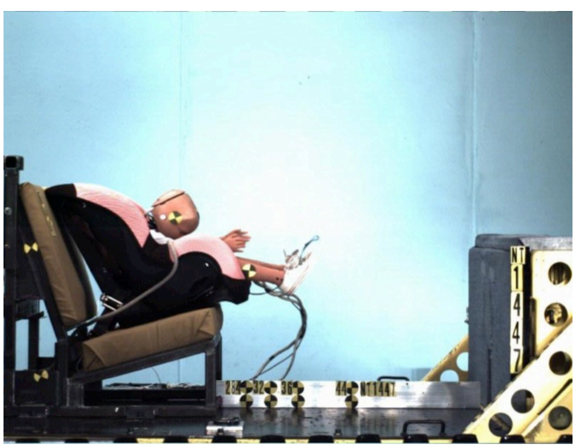
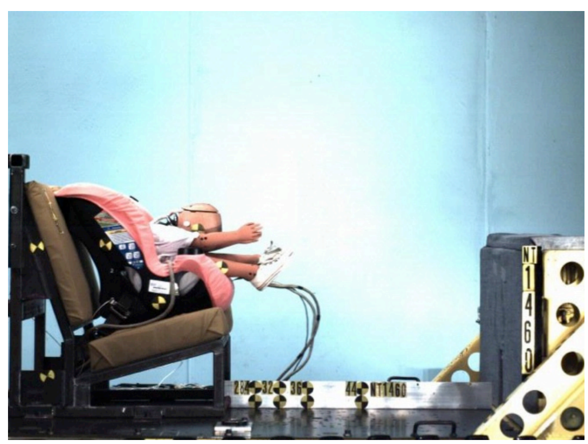

Figure 9. Illustration of CRS type effect illustrating systematic kinematic differences between the Evenflo (left) and Cosco (right) convertibles

Figure 10 compares peak excursion photos for correct installation (left) and the no tether, loose installation, loose harness condition (right) for the same CRS model and shows the large difference in ATD forward movement.

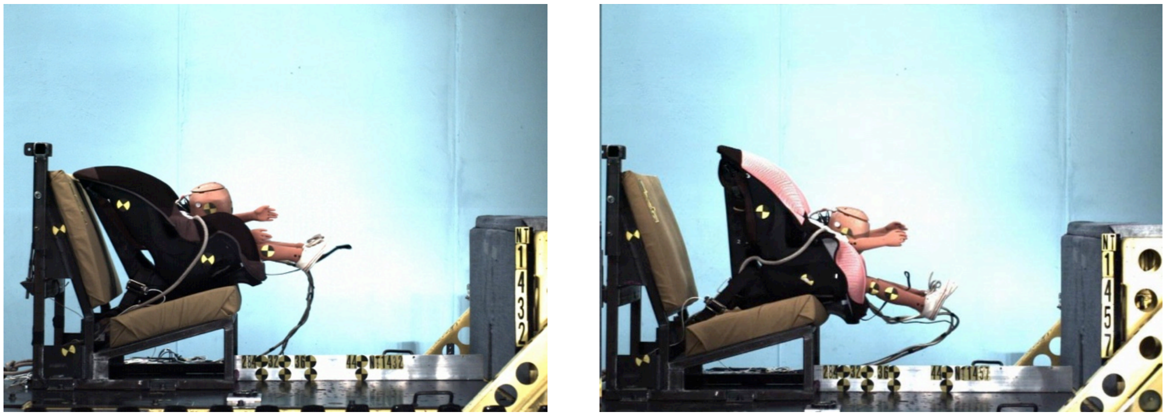

Figure 10. Peak of action image comparing maximum forward excursion with no misuse (left) and with loose harness, loose installation and no tether (right) in Evenflo convertible

Figure 11 shows the knee excursion versus head excursion results for the forward-facing tests by CRS type, by seatbelt or LATCH belt, by chest clip use, and by misrouting. Figure 12 shows results according to tether use, harness tightness, and installation tightness. Each plot contains lines indicating the allowable head excursion threshold of 720 mm and knee excursion limit of 915 mm. Where appropriate, linear trend lines are included.

The CRS plot shows how the Cosco runs are shifted relative to tests run with the other two CRS but that all products have similar trends over the range of conditions. The tests run with either seatbelt or LATCH belt also span the full range of data. The majority of tests run without the chest clip or with the belt routed incorrectly through the rear-facing belt path still met head and knee excursion limits.

The graph of tether conditions shows the most striking results. Only one test with correctly used tether failed to meet the excursion limits, and that was a test where both the harness and installation were loose. The tests with correctly used tether consistently had the lowest head and knee excursions, while those with no tether use or loose tether comprised most of the tests that did not pass excursion limits. For the harness conditions, about one-third of the loose harness conditions failed, while two-thirds passed. The two tests with snug harness that failed had loose or no tether and a loose installation. For the tests evaluating installation tightness, about half failed and half met excursion limits. The tight installation that failed did not use a tether and had a loose harness. Most of the loose installations that passed used the tether correctly.

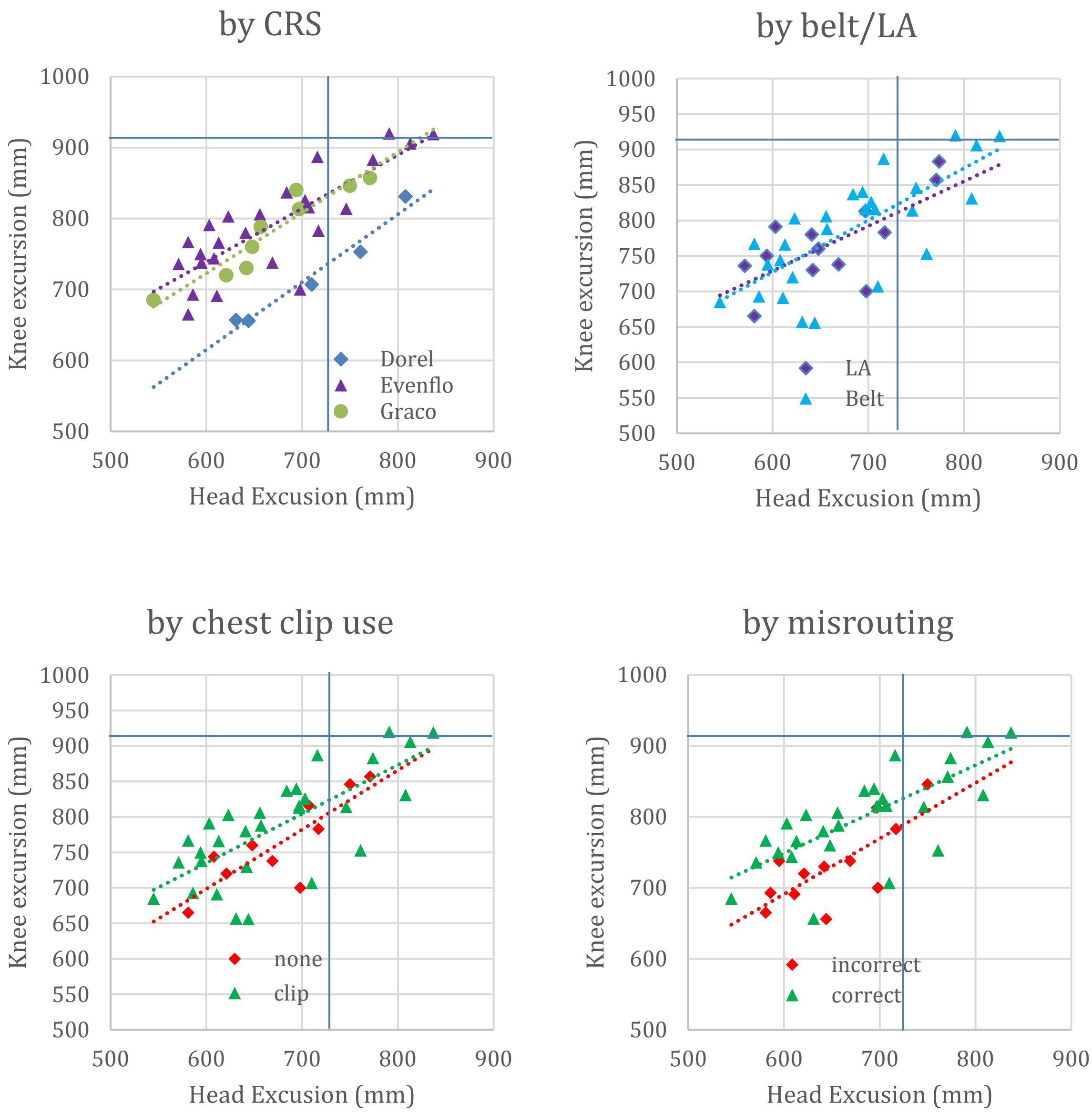

Figure 11. Knee excursion versus head excursion in forward-facing tests by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting

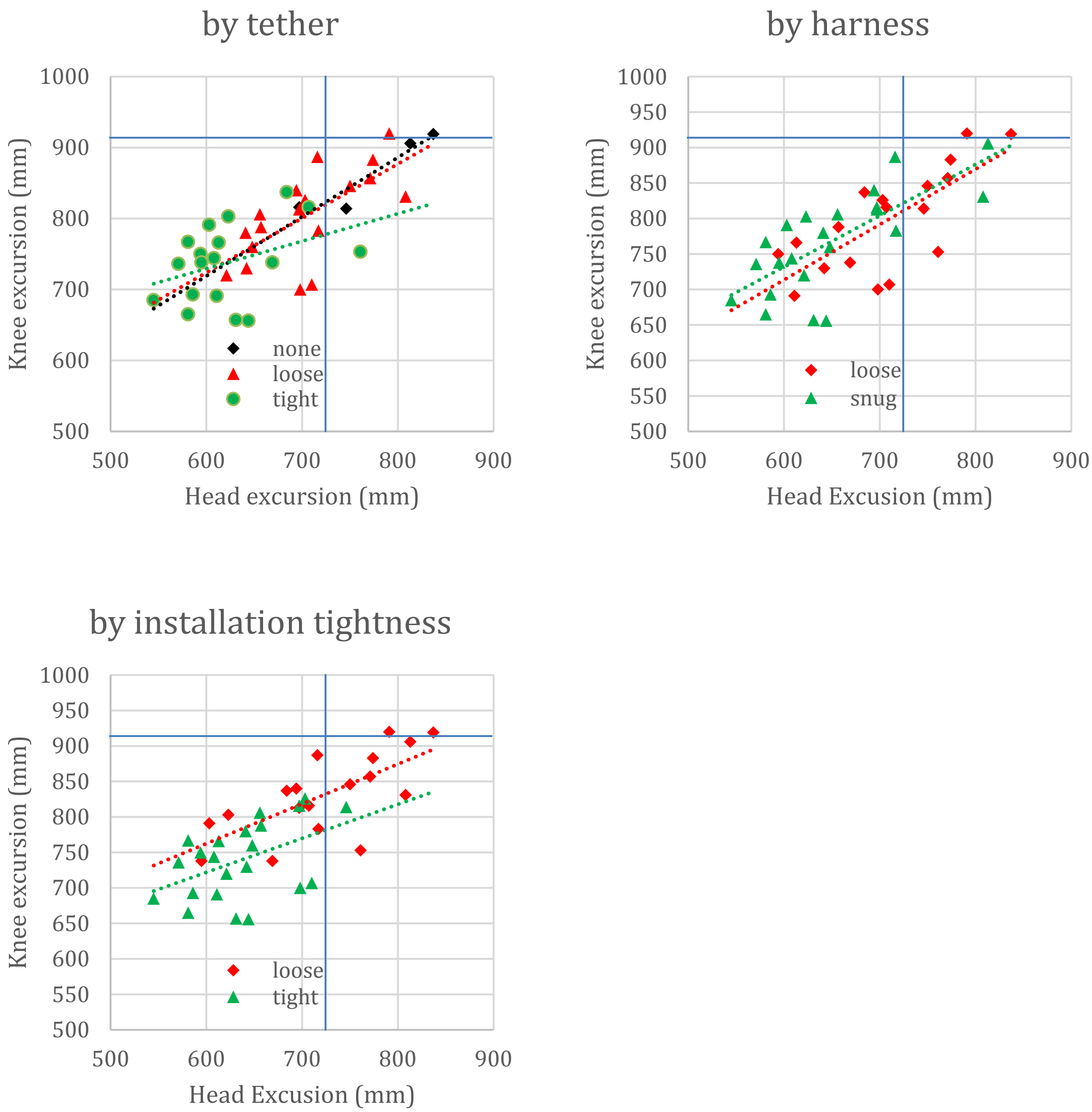

Figure 12. Knee excursion versus head excursion in forward-facing tests by tether use, loose installation, and loose harness

For the forward-facing test conditions, the chest 3ms clip data are plotted versus HIC (36) data according to CRS, seatbelt versus LATCH belt, chest clip use, and misrouting in Figure 13. Results for tether use, harness tightness, and installation tightness are shown in Figure 14. Plots include lines demarking the limits of 60 *g* and HIC of 1000. As expected, the two values show a general relationship because decoupling the occupant from the test bench through loose installation and loose harness tends to raise the overall ATD accelerations.

The acceleration responses by CRS type and by seatbelt versus LATCH belt generally overlap across the range of conditions, with slight shifts in trends by CRS. Most of the conditions where chest clip was not used or the belt was misrouted met the acceleration limits. The two tests that did not had no chest clip, misrouting, a loose harness, and loose tether.

Again, the tether results show the most drastic change with conditions. Tests with the tether tight consistently had the lowest head and chest accelerations, while those with tether loose or absent had the highest. The test with tight tether at the chest acceleration limit also had loose harness and loose installation.

Harness tension (i.e., harness loose vs. harness snug) did not significantly affect the occupant injury responses. Correct tether use (i.e., using a tether with tight tension) had a significant beneficial effect on HIC 36 and Chest Acceleration occupant injury responses. Tests with loose installation generally had higher values of chest acceleration compared to those with tight installation.

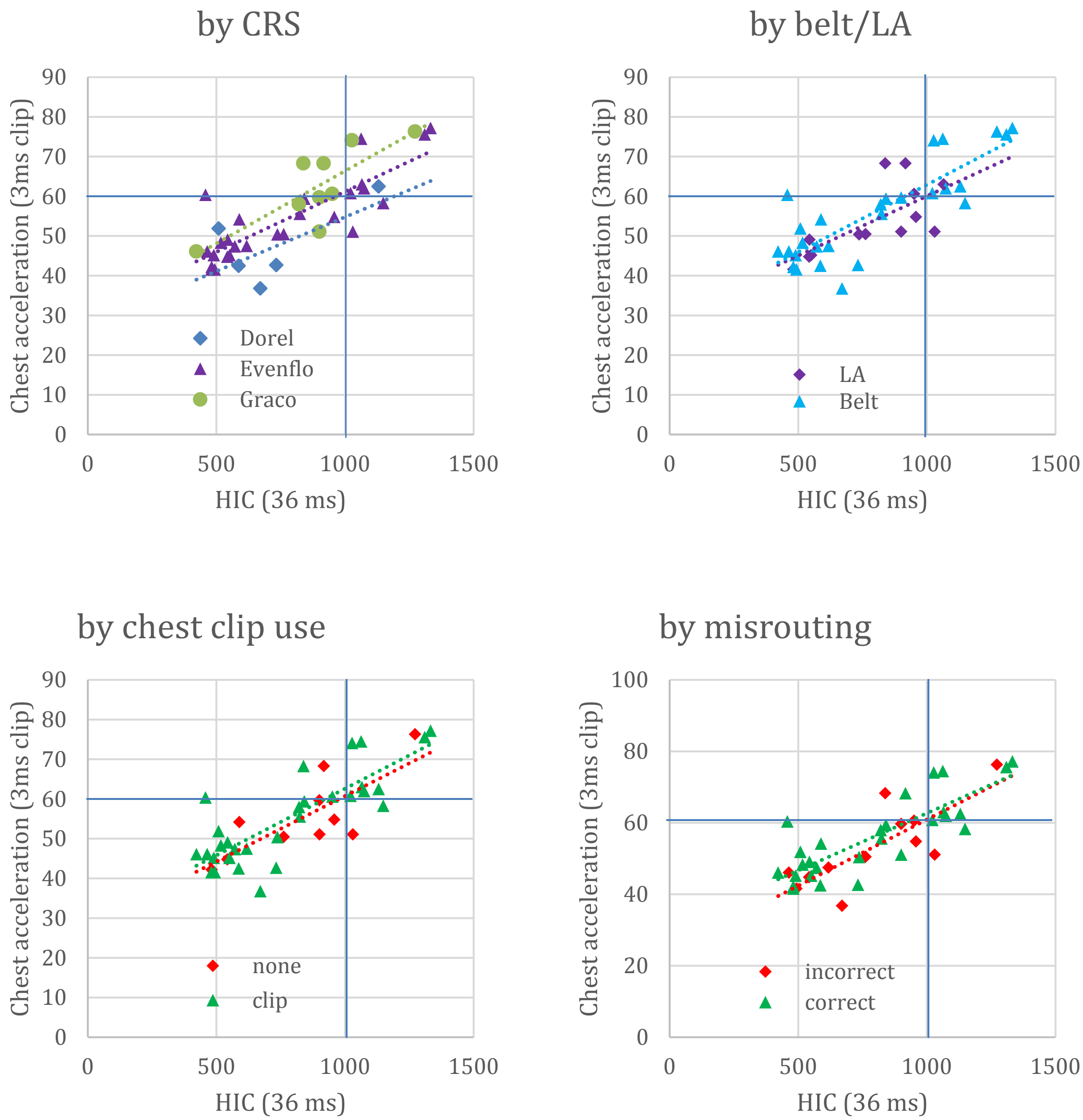

Figure 13. Chest acceleration versus HIC (36) in forward-facing tests by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting

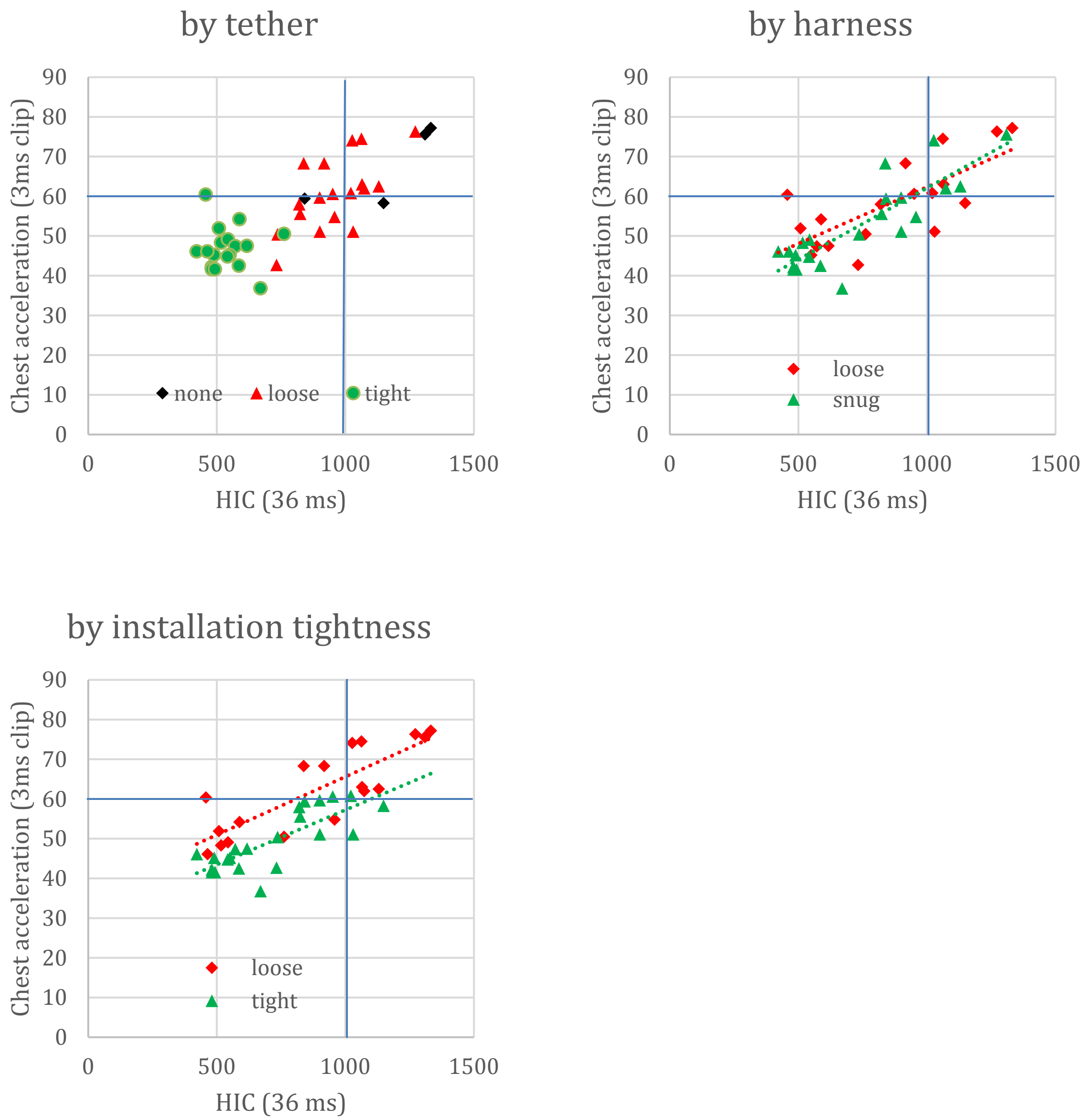

Figure 14. Chest acceleration versus HIC in forward-facing tests by tether use, loose installation, and loose harness

Rear-facing analysis

For the rear-facing data, the only misuse with a significant main effect was incorrect belt path. When CRS were secured rear-facing using the forward-facing belt path the average increase in forward CRS rotation was 70 degrees ($P<0.0001$) over the correct use condition. No two-way interactions were found. Figure 15 compares maximum forward rotation with each belt path.

Figure 15. Comparison of peak forward rotation of CRS with correct belt path use (left) and incorrect belt path use (right)

Figure 16 plots the maximum versus initial CRS seatback angle by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting, while Figure 17 plots results by recline angle, harness tightness, and installation tightness. The plots also contain a line marking the 70-degree rotation limit of FMVSS 213. As indicated by the statistical analysis, the only notable trend is misrouting, where all tests failed the limit by more than 40 degrees. The CRS plots shows that each product tested is designed to have a different initial position. When reviewing initial recline, there is a trend among passing tests that when a CRS is initially too upright, it will have a lower final angle than a CRS placed initially too reclined.

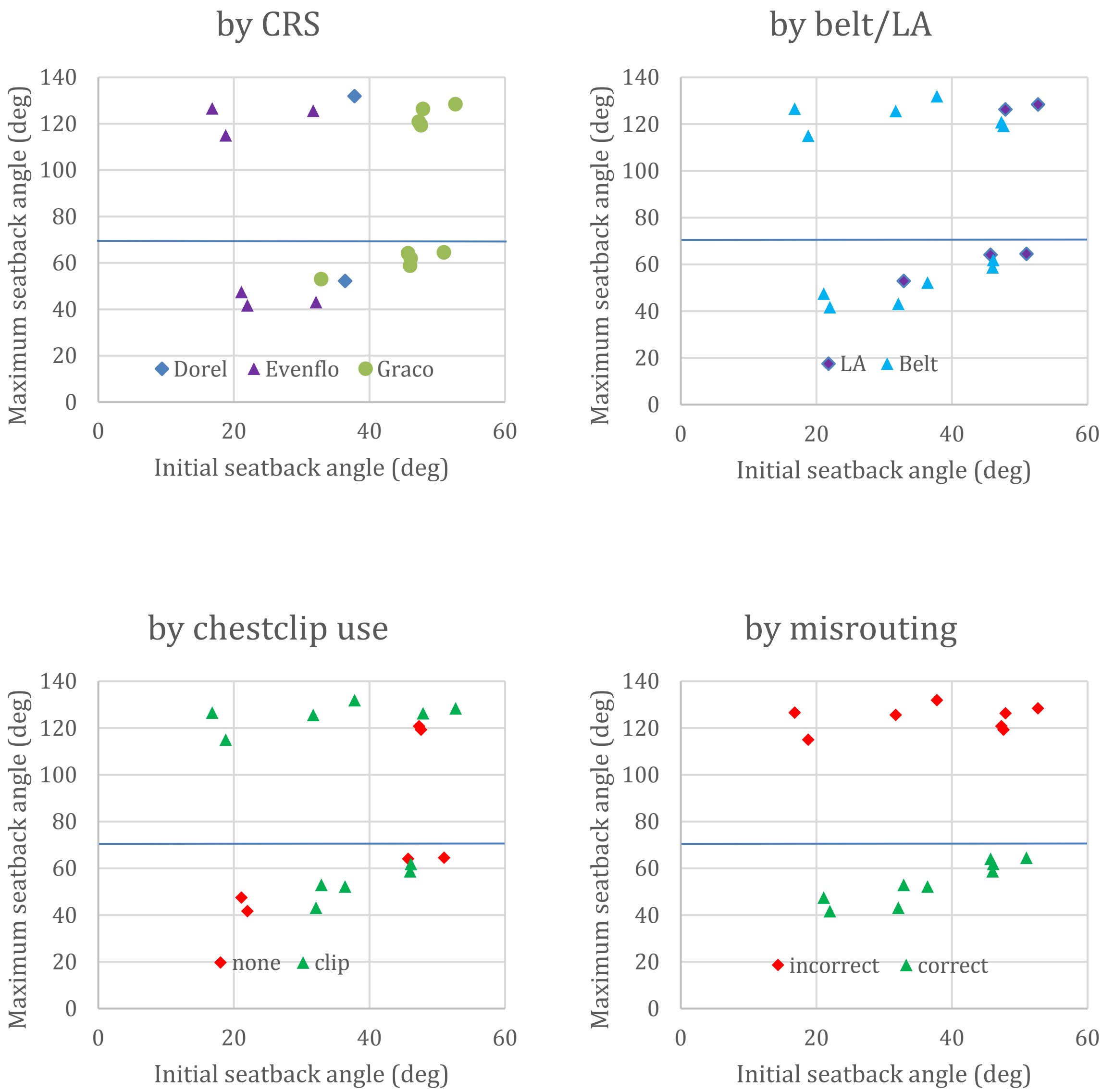

Figure 16. Maximum seatback rotation angle versus initial seatback angle for rear-facing tests by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting

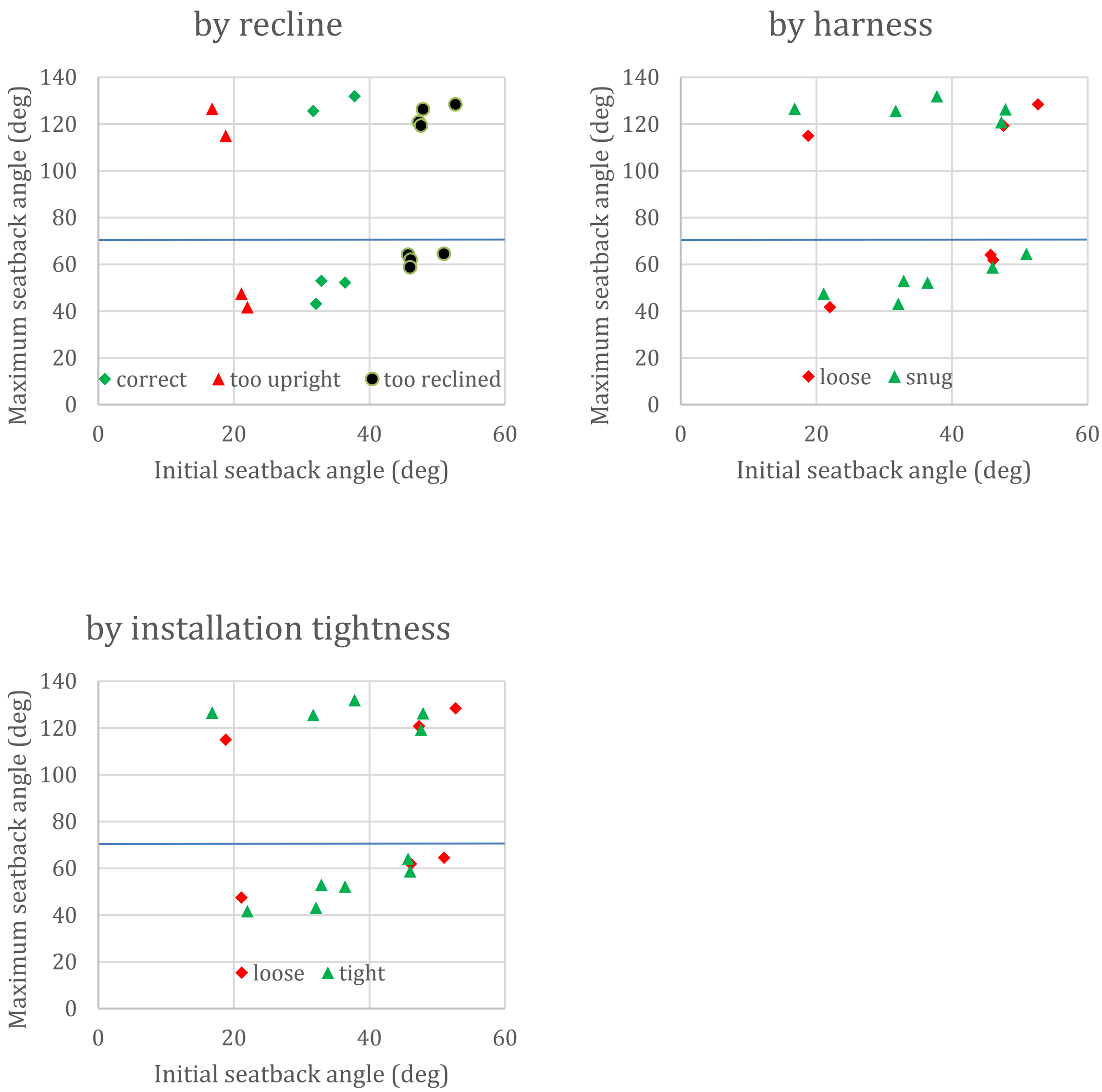

Figure 17. Maximum seatback rotation angle versus initial seatback angle for rear-facing tests by recline angle, loose installation, and loose harness

Chest acceleration versus HIC is plotted for the rear-facing tests in Figure 18 by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting. Results for recline angle, harness tightness, and installation tightness are shown in Figure 19. Plots also contain lines indicating FMVSS 213 limits of 60 g and HIC of 1000. The three tests where excessive HIC was caused by contact with the nonrealistic floor of the test bench are not included on the graphs.

Overall, chest acceleration generally increases with increasing HIC. The three tests with the highest HIC are conditions with belt misrouting. The other two tests that failed HIC had a loose harness coupled with no chest clip and too upright and loose harness coupled with too reclined and loose installation. Two other tests that met HIC but failed chest criteria were both too reclined; one of these also had a loose installation and no chest clip. Though not statistically significant, a less upright installation tended to produce higher head and chest acceleration measures as the seatback is positioned to provide less support to the ATD head and chest.

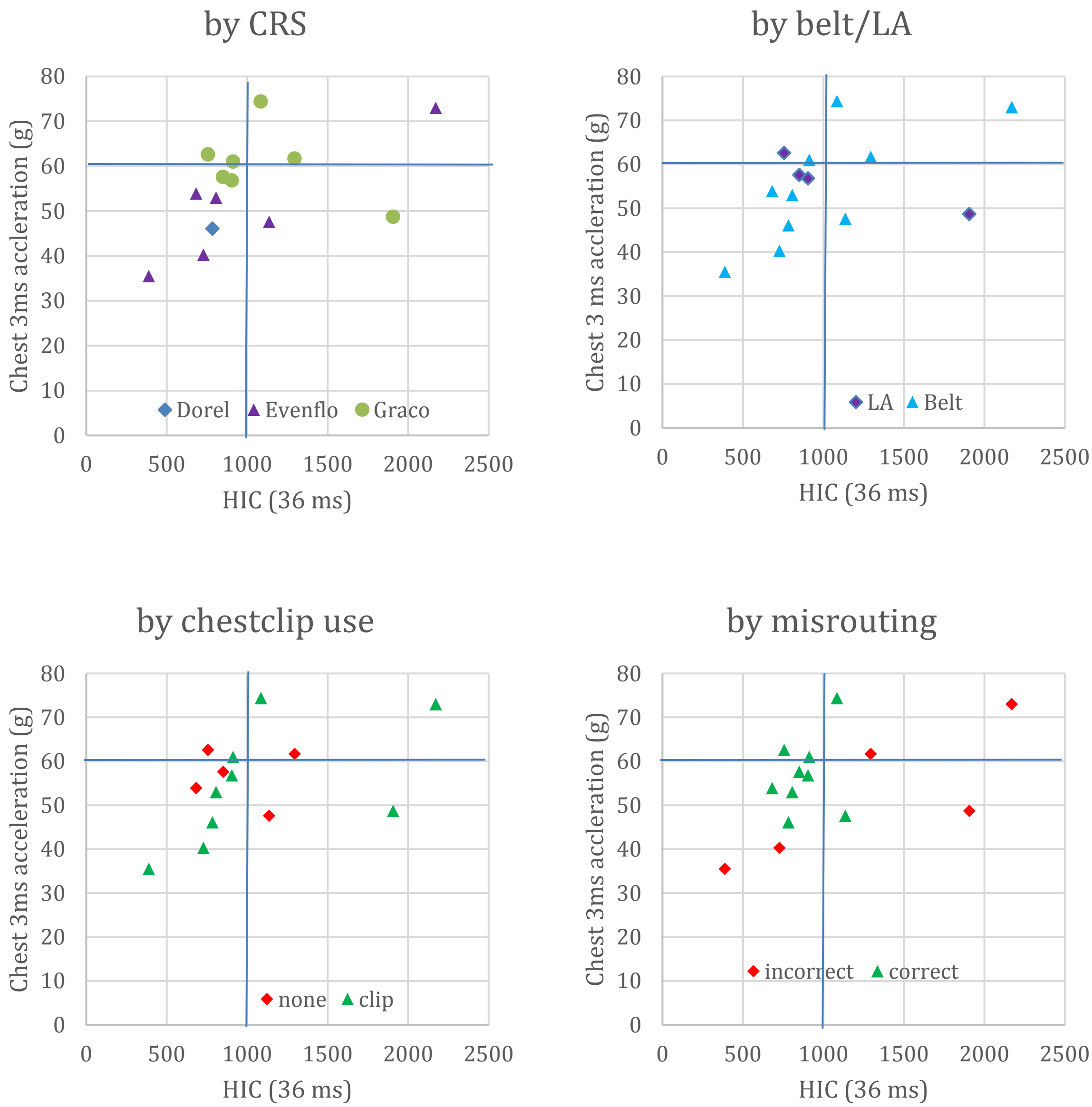

Figure 18. Chest acceleration versus HIC in rear-facing tests by CRS, seatbelt versus LATCH belt, chest clip use, and misrouting

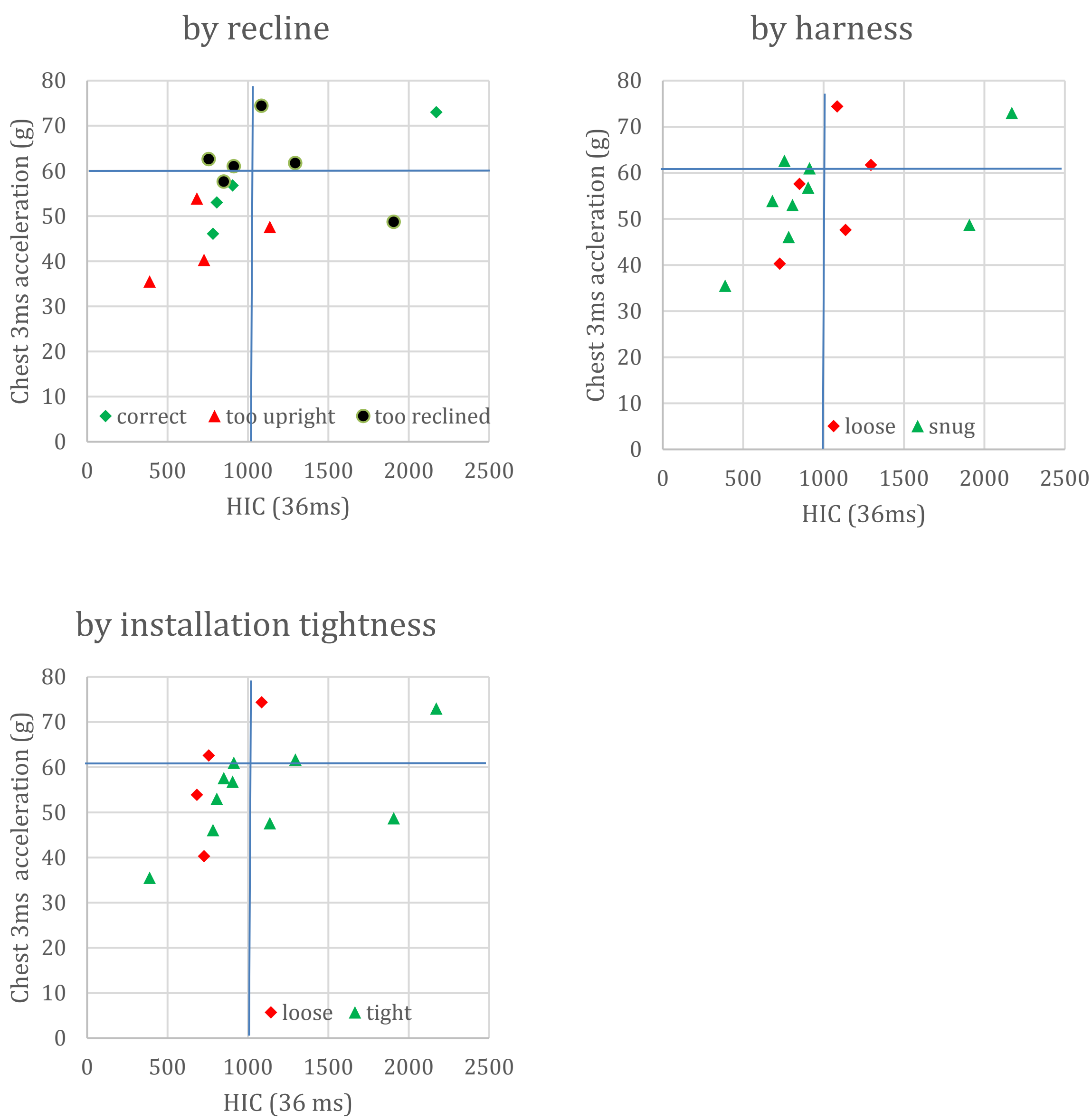

Figure 19. Chest acceleration versus HIC in rear-facing tests by recline angle, loose installation, and loose harness

Examples of Observed Structural Issues

Five CRS structural issues were observed in the series and example photos are shown in Figure 20 through Figure 24. In two forward-facing tests (NT1415 and 16) with the incorrect belt path condition, a corner of the belt path cracked and trapped the lower anchor (LA) belt webbing (Figure 20). In forward-facing runs NT1451, 52, 53, all with a loose tether condition, the recline adjuster foot protruded into the shell (Figure 21). In rear-facing runs NT14 33, 34 and 35 where the initial CRS angle was too upright, cracks in the shell at the belt path were observed (Figure 22). In run NT1438 the crotch strap pulled out of the shell (Figure 23). In run NT1463 the tether strap pulled out of the CRS shell (Figure 24).

Figure 20. Example of belt path fracture trapping LA webbing

Figure 21. Example of recline adjuster foot protruding into CRS shell in loose tether condition

Figure 22. CRS shell cracking in rear-facing runs with too upright orientation

Figure 23. Crotch strap pulled through CRS shell

Figure 24. Tether strap pulled through CRS shell

Discussion

This study quantified the effects of common CRS misuses and misuse combinations on ATD response measures, with a particular focus on forward movement, since this is associated with observed head, neck and face injuries for restrained children in the field. For forward-facing installations, misuses that decrease the occupant coupling with the vehicle, including loose harness, loose installation, and loose/no tether are all important. This finding suggests that CRS designed with features to counteract these misuses, like aids that improve installation tightness, and harnesses that include retractor features, could facilitate optimal performance by the CRS in the real world.

A properly used tether reduces forward head excursion by 150 mm on average and also leads to lower accelerations. The current study demonstrates that correct use of a tether can compensate for the other two most common errors of loose installation and loose harness. The tether's efficacy to inhibit head movement is especially important given the data on head contact injuries in nominally restrained occupants. Some studies have not considered the lack of tether to be misuse, since CRS must meet excursion limits when a tether is not used. Results of the current study indicate that both tether misuse and non-use significantly affect occupant responses.

For rear-facing installations, the only misuse with a large effect was incorrect belt path. For rear-facing, a misrouted belt significantly decrements CRS performance by allowing greater forward rotation of the CRS. This effect is likely more pronounced with LA only or lap belt only. While the Authors did not test with a lap and shoulder belt, the Authors postulate that the addition of a shoulder belt segment would help to restrain CRS rotation.

In general, the rear-facing tests were less prone to poor performance under user CRS misuse. This likely plays a role in the effectiveness of using rear-facing CRS compared to forward-facing CRS. Given that the current study indicates less severe consequences of common misuses for rear-facing compared to forward-facing, these data support current recommendations to keep children rear-facing until they outgrow their rear-facing CRS.

Limitations of this study are that misuse was evaluated with only three common CRS models, only convertible child restraints were evaluated, and only one size of ATD was used in all tests. In addition, the work did not examine errors associated with improper CRS selection and premature graduation that are both prevalent misuse modes in the field. Only common misuse types were addressed.

Conclusions

The main conclusions of this project are:

- Educational efforts that focus on tight tethers may have an oversized influence on child safety, because the results of this study indicate that tight tethers can mitigate the effects of other common misuses.
- Because common misuses generally had lower effect on performance in rear-facing tests compared to forward-facing conditions, the results support current recommendations to keep children rear-facing as long as possible.

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